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MODULATION AND CODING TECHNOLOGY FOR DEEP SPACE AND SATELLITE APPLICATIONS

(Invited Paper)

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Abstract

Modulation and coding research and development activities at the Jet Propulsion Laboratory currently emphasize the following two areas: Deep Space Communications Systems and advanced near-earth Commercial Satellite Communications Systems. The Deep Space Communication channel is extremely signal-to-noise ratio limited and has long transmission delay. The near-earth (GEO and LEO) satellite channel is bandwidth limited with fading and multipath.

Recent code-search efforts at JPL have found a long constraint, low rate convolutional code (15, 1/6) which, when concatenated with a 10 bit Reed-Solomon (RS) code provides a 2.1 dB gain over that of the Voyager Spacecraft - the current standard. The new JPL code is only 2 dB from the theoretical Shannon limit. A flight qualified version of the (15, 1/6) convolutional encoder has been implemented on the Galileo Spacecraft - to be launched later this year. This will result in increased data return from Jupiter in the 1990s. A decoder for this class of codes is under development at JPL using parallel processing algorithms and VLSI technology. An Image Statistics Decoder (ISD) has been developed, which uses the source statistics of the image (or picture) to modify the standard Viterbi decoding algorithm in decoding convolutionally encoded Voyager images. This ISD, which provides as much as 3 dB coding gain in the region of interest, will be used as a backup decoder for Voyager's Neptune Encounter in August 1989. Other JPL activities in modulation and coding for deep space applications will also be discussed.

NASA has played a leading role in the development of satellite based, fixed and mobile communications for the U.S. with the work at JPL focused on the L-band, mobile link. This link has necessitated the development of a new highly bandwidth and power efficient digital modem. A unique 4.8 kbps, rate 2/3 8 DPSK Trellis Coded Modulation (TCM) scheme has been derived and implemented which is robust in the presence of Rician fading, and doppler shifts up to 10% of the transmitted symbol rate (2.4 ksps) for a basic 5 kHz channel width. A compatible 4.8 kbps speech compressor has also been developed which achieves good intelligibility, and sound "natural" at a low implementation complexity. New JPL activities in the Satcom area include: meeting personal communications needs at the turn of the 21st Century, by exploiting Ka-band; and developing the subsystem technology for the interconnection of satellite resources by using high rate optical inter-satellite links.

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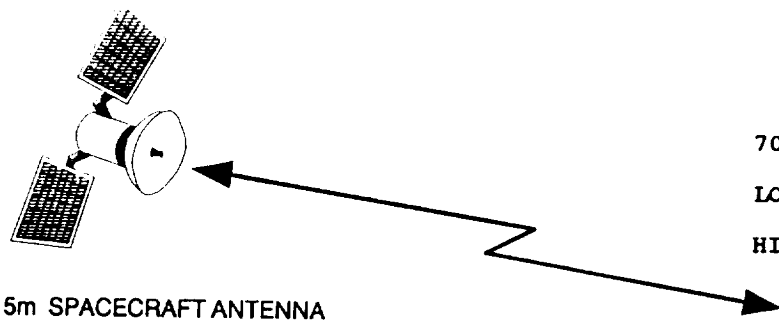
DEEP SPACE COMMUNICATIONS



- TELEMETRY IS THE PROBLEM
  - HIGH DATA RATES FOR IMAGING
  - LOW SNRs
- CODING IS CRITICAL TO TELEMETRY
  - ENCODERS MUST BE SMALL, LIGHT, LOW POWER
  - DECODERS TEND TO BE VERY COMPLEX

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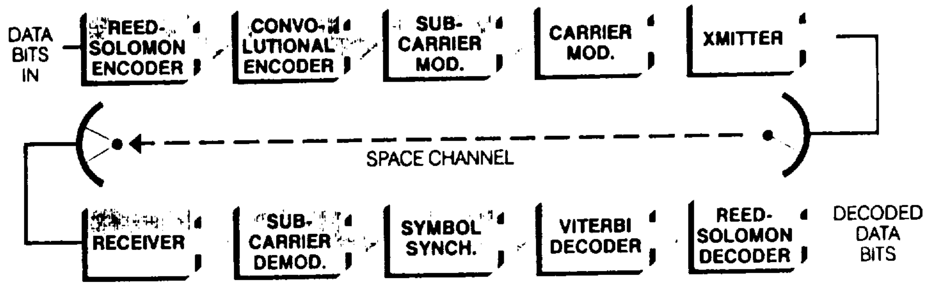
THE 2 dB CODE SEARCH



CONCATENATED CODING SYSTEM BLOCK DIAGRAM

- BASELINE PERFORMANCE: BER = 10^{-6}
- BASELINE CODE: VOYAGER AT URANUS
  (7, 1/2) + 8-bit RS — Required E_b/N_0 = 2.53 dB

- SIMULATED PERFORMANCE OF CONCATENATED CODES WITH 10-bit REED-SOLOMON OUTER CODE

INNER CONVOLUTIONAL CODES	E_b/N_0	
(13, 1/4)	0.84 dB	
(13, 1/5)	0.68 dB	
(14, 1/4)	0.74 dB	
(14, 1/5)	0.57 dB	
(15, 1/4)	0.80 dB	
(15, 1/5)	0.50 dB	
(14, 1/6)	0.47 dB	
(15, 1/6)	**0.42 dB**	**= 2.11 dB Gain**

We search for codes that will provide significant improvement, say 2 dB, over our Voyager baseline system (7, 1/2) convolutional code as the inner code (with Viterbi decoding,) and an 8-bit (255, 223) Reed-Solomon code as the outer code. We use the criterion of minimizing required bit SNR, for a given value of desired BER, for the goodness of code. The code space is astronomically large for long constraint length low rate convolutional codes. Using educated guesses combined with the idea that good codes generate good codes, we selectively search for good codes. These codes performance are determined by computer simulation. The decoder complexity is manageable by using concurrent processing technique and VLSI technology.

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IMAGE STATISTICS DECODER (ISD)

INFORMATION SYMBOLS $(b_1, b_2, \ldots, b_n)$

CODED SYMBOLS $(s_1, s_2, \ldots, s_m)$

RECEIVED SYMBOLS $(r_1, r_2, \ldots, r_m)$

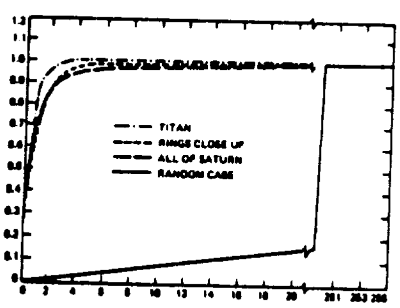
$$D_j = |b_j - b_{j-1}|$$

σ^2 FUNCTION OF BIT SNR

ISD MINIMIZES

$$\underbrace{\sum_i \frac{(r_i - s_i)^2}{\sigma^2}} - \sum_j \ln P(b_j | D_j)$$

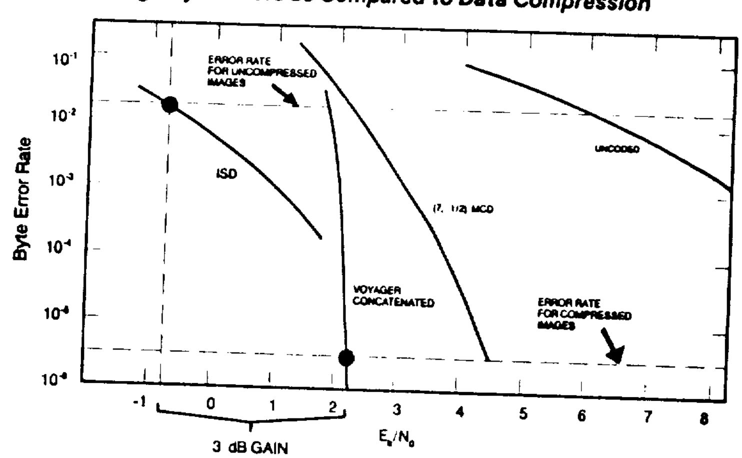
MINIMIZE THIS TERM
ONLY, IF INFORMATION BYTES
ARE ASSUMED INDEPENDENT



Distributions of Adjacent Pixel Variation D for 3 different Voyager images and the random case

ISD PERFORMANCE

Image Byte Errors as Compared to Data Compression



Maximum likelihood (or Viterbi) assumes that all codewords are a priori equally likely to be transmitted, this decoding scheme retrieves the most likely sent codeword. In some cases, though, codewords are not all equally likely to be transmitted. In Voyager images, for example, pixel to pixel variations are not completely random. They are much more likely to be small than large. In this case, a decoder which makes use of the source statistics should perform better than a Viterbi decoder. (Image compression uses these statistics to lower the transmission rate and thus raise symbol SNR, but some Voyager images are sent uncompressed because of spacecraft limitations; also, an alternative would be valuable in the unlikely event of a data compressor failure before Neptune encounter in 1989.) This is exactly what our ISD does. It amounts to an additional term to the usual Viterbi decoder.

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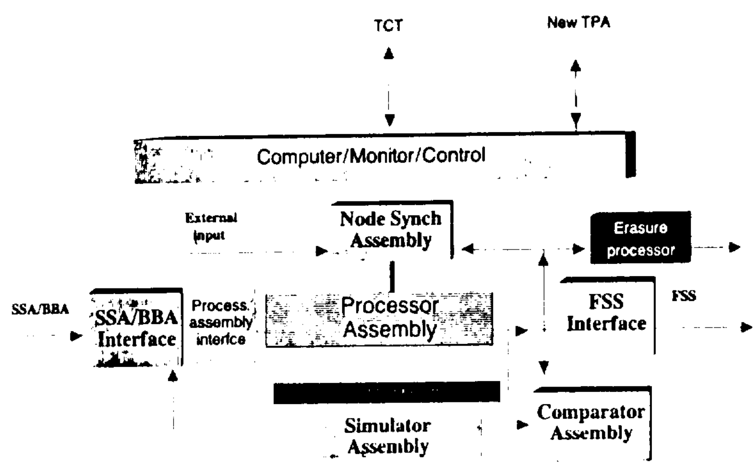
DE CODER

- Objectives:
  - ✓ Develop, Build, test, and demonstrate a prototype Viterbr decoder for the DSN capable of using (15,1/6) convolutional codes, leading to flight tests with Galileo's (15,1/4) encoder
- Requirements:
  - ✓ **Performance:**
    - **Constraint length up to 15, programmable**
    - **Code rate 1/2 to 1/6, programmable**
    - **Data rate 1.1 Mbit/s (Galileo 115, 134 Kb/s)**
    - **Node synch using frame synch pattern, programmable**
    - **Node synch using metric growth rate**
    - **Include full self-test capability**
  - ✓ DSN Compatible



The major complexity driver of the decoder is constraint length, since the amount of hardware is roughly proportional to the number of states which is 2 to the (K-1), where K is the constraint length. Hence, a decoder for K = 15 is approximately 256 times more complex than a decoder for K = 7. Using concurrent processing techniques, such a complex decoder can be built, with current VLSI technology, within reasonable size limitations. The decoder is under development. It will be ready in 1991, before Galileo reaches Jupiter in 1995.

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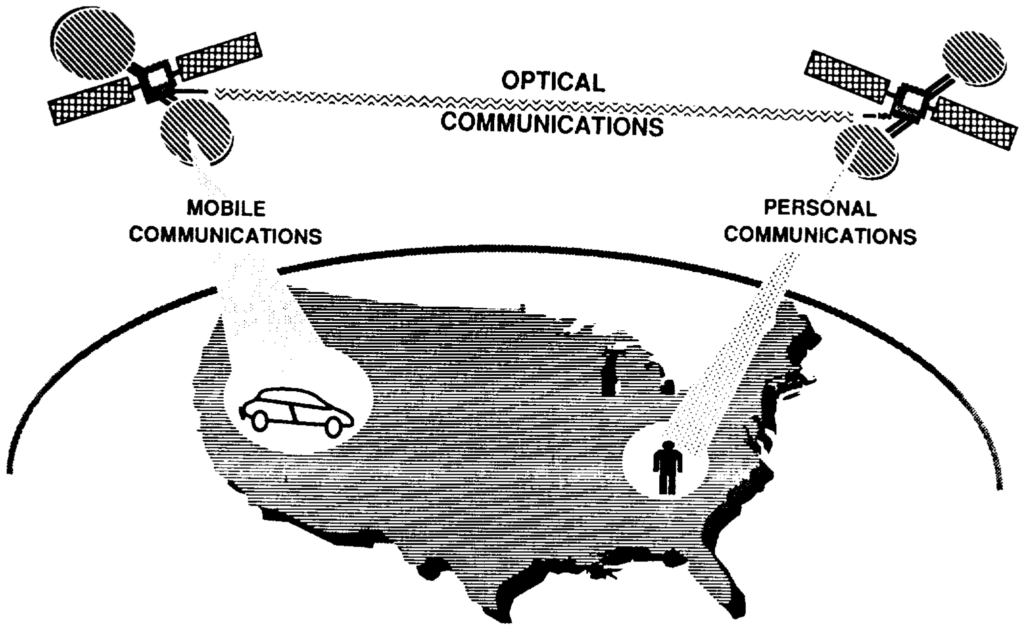
MODULATION & CODING FOR SATCOM APPLICATIONS



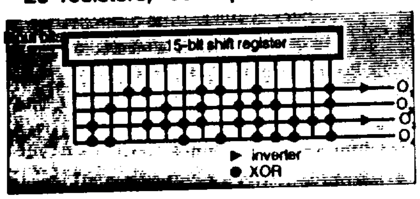
MODULATION & CODING ARE CRITICAL TO EFFICIENT USE OF SATELLITE RESOURCES

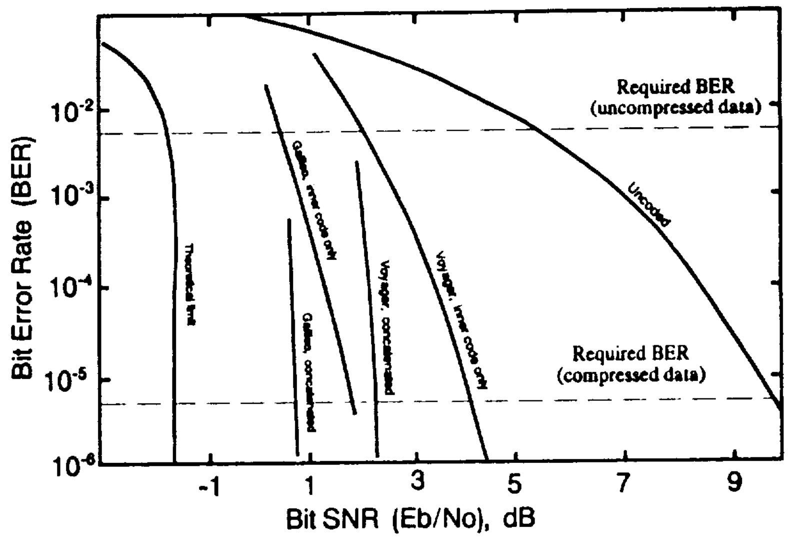
- BANDWIDTH
- POWER
- ORBITAL SLOT

Performance of Galileo Codes

The new encoder....

✔ 26 resistors, 39 capacitors, 20 ICs





Due to the Space Shuttle Challenger's accident, the launch of the Galileo spacecraft to orbit Jupiter (and to drop a probe into the atmosphere of Jupiter) was delayed. The delay will require new trajectory that makes the communication distance from Galileo to Earth much longer than the original trajectory. We install a (15, 1/4) convolutional code on Galileo -- the RS code remains to be 8-bit (255, 223). This gives about 1.5 dB over the original (7, 1/2) code. This provides significant performance improvement with minimal impact on the existing Galileo design.

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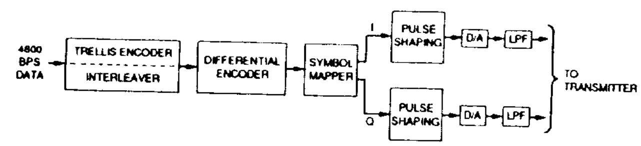
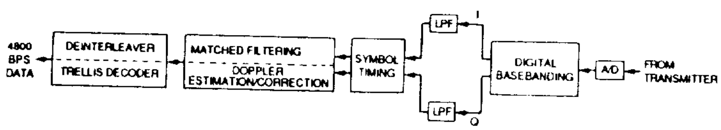
4800 BPS 8DPSK TCM MODEM

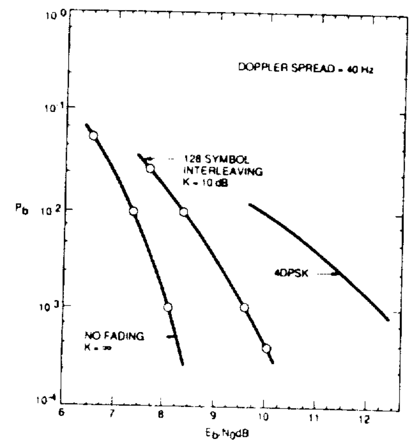
MODULATOR



DEMODULATOR



SIMULATION RESULTS



THE MSAT-X 8DPSK TCM MODEM IS A POWER AND BANDWIDTH EFFICIENT, NARROWBAND MODEM DESIGNED TO COMBAT THE PROPAGATION EFFECTS OF THE L-BAND LAND-MOBILE SATELLITE CHANNEL. THE TYPICAL CHANNEL IMPAIRMENTS CONSIST OF MULTIPATH (RICIAN) FADING AND VEGETATIVE SHADOWING. THE MODULATOR TRELLIS ENCODES, INTERLEAVES, AND DIFFERENTIALLY ENCODES THE INPUT DATA BEFORE CONVERTING THE DATA TO PULSE SHAPED I AND Q WAVEFORMS FOR TRANSMISSION THROUGH THE CHANNEL. THE DEMODULATOR IS IMPLEMENTED WITH A FEEDFORWARD ARCHITECTURE TO COMBAT THE EFFECTS OF FADES, AND EMPLOYS DIFFERENTIAL DETECTION USING A NOVEL MATCHED FILTERING AND DOPPLER ESTIMATION/CORRECTION ALGORITHM TO RECOVER THE TRANSMITTED DATA. THE DATA IS THEN DEINTERLEAVED AND DECODED TO PRODUCE AN ESTIMATE OF THE BASEBAND DIGITAL DATA. EXPERIMENTAL RESULTS HAVE SHOWN THAT THE CURRENT IMPLEMENTATION OF THE MODEM PERFORMS WITHIN 1 dB OF SIMULATION RESULTS.

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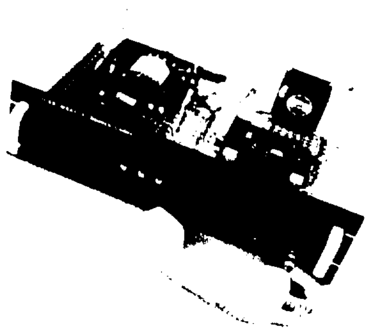
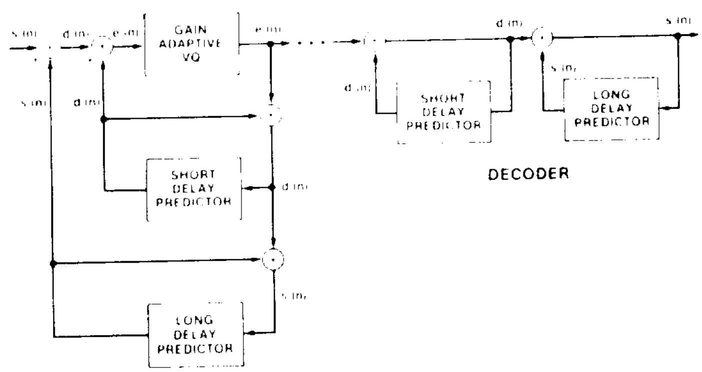
JPL 4.8 kbps DIGITAL SPEECH COMPRESSION



VECTOR ADAPTIVE PREDICTIVE CODING
UC-SANTA BARBARA



ENCODER

UCSB VECTOR ADAPTIVE PREDICTIVE CODING

THE VAPC ALGORITHM COMBINES LINEAR PREDICTION WITH VECTOR QUANTIZATION. ADAPTIVE LINEAR PREDICTORS ARE UTILIZED TO REMOVE REDUNDANCY FROM THE SPEECH WAVEFORMS. THE REMAINING PREDICTION ERROR IS THEN QUANTIZED BY EMPLOYING VECTOR QUANTIZATION. THE USE OF VECTOR QUANTIZATION ALLOWS THE CODING OF THE ERROR SIGNAL AT RATES BELOW ONE BIT PER SAMPLE – AN ESSENTIAL CHARACTERISTIC FOR LOW BIT RATE COMPRESSION.

THE ENCODING PROCESS BEGINS WITH A LONG DELAY PREDICTOR TO REMOVE THE REDUNDANCY CORRESPONDING TO THE PITCH STRUCTURE OF SPEECH. A SHORT DELAY PREDICTOR FOLLOWS TO REMOVE INFORMATION ROUGHLY CORRESPONDING TO THE FORMANT STRUCTURE OF SPEECH. THE REMAINING ERROR SIGNAL IS QUANTIZED AS TIME SEQUENCES OR VECTORS BY EXHAUSTIVELY COMPARING THE ERROR VECTORS TO STORED VECTORS AND CHOOSING THE STORED VALUES THAT MINIMIZE THE MEAN SQUARED ERROR.

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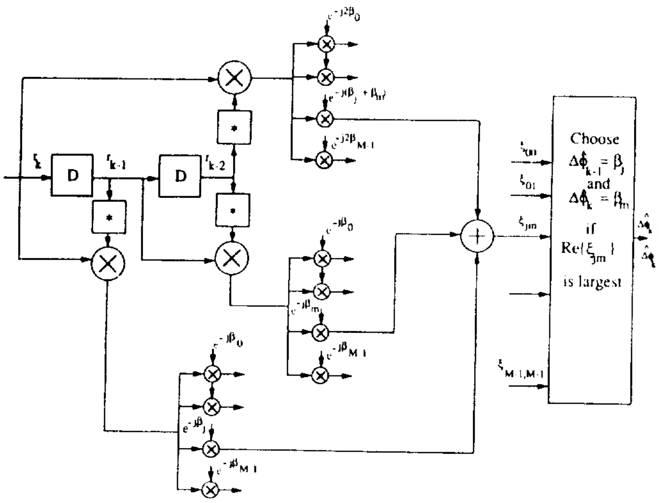
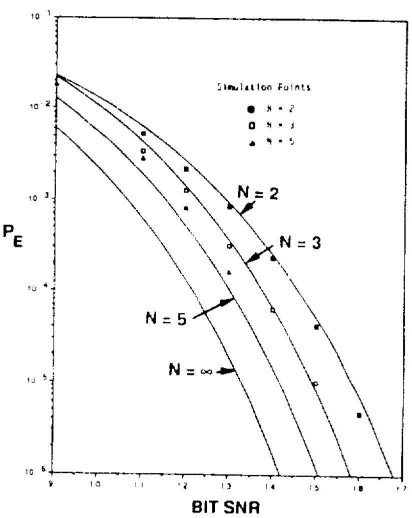
MULTIPLE SYMBOL DIFFERENTIAL DETECTION OF MPSK



MULTIPLE BIT DETECTOR
N = 3



8 DPSK PERFORMANCE
N = 2, 3, 5, ∞ (COHERENT)

CONVENTIONAL DIFFERENTIAL DETECTION OF MPSK (MDPSK) USES THE PREVIOUS SYMBOL AS A DEMODULATION REFERENCE FOR THE CURRENT SYMBOL. THE ERROR PROBABILITY PERFORMANCE OF BINARY DPSK VARIES AS $EXP(-E_S/N_0)$.

MULTIPLE SYMBOL DIFFERENTIAL DETECTION OF MPSK OBSERVES THE RECEIVED SIGNAL PLUS NOISE OVER N (MORE THAN TWO) SYMBOL INTERVALS. A MAXIMUM-LIKELIHOOD SEQUENCE ESTIMATION ALGORITHM IS USED TO DETECT THE CURRENT SYMBOL USING ALL OF THE PREVIOUS SYMBOLS. IT REQUIRES IDENTICAL DIFFERENTIAL ENCODING OF THE INPUT DATA PHASES AS FOR CONVENTIONAL (N=2) DIFFERENTIAL DETECTION. THE ERROR PROBABILITY VARIES BETWEEN THAT FOR CONVENTIONAL DIFFERENTIAL DETECTION AND COHERENT DETECTION. IN THE LIMIT OF INFINITE SYMBOL OBSERVATION, THE ERROR PROBABILITY BECOMES IDENTICAL TO THAT OF COHERENT DETECTION OF MPSK WITH DIFFERENTIALLY ENCODED INPUT PHASES. IN PRACTICE, WITH ONLY A FEW ADDITIONAL OBSERVATION INTERVALS, ONE CAN APPROACH COHERENT DETECTION PERFORMANCE.

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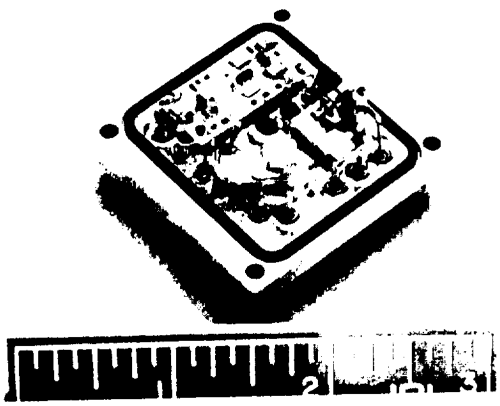
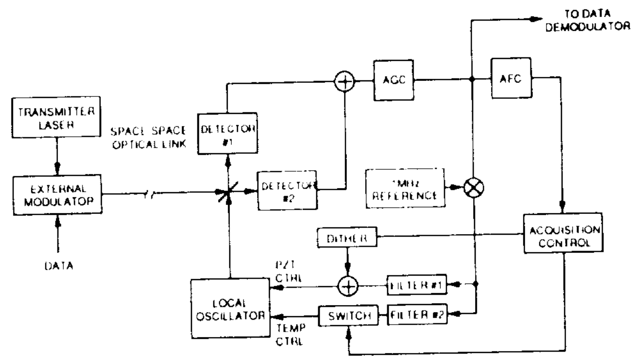
ADVANCED OPTICAL MODULATION



FREQUENCY STABILIZED LASER WITH TEMPERATURE AND PIEZO-ELECTRIC TUNING CAPABILITIES



BLOCK DIAGRAM OF A COHERENT OPTICAL LINK

THIS WORK IS FOCUSED ON THE KEY TECHNOLOGIES REQUIRED FOR THE DEVELOPMENT OF COHERENT FREE SPACE OPTICAL COMMUNICATIONS. RECENT DEVELOPMENTS OF FREQUENCY-STABILIZED SOLID STATE LASERS WILL PERMIT THE REALIZATION OF PHASE COHERENT FREE-SPACE OPTICAL COMMUNICATION SYSTEMS PREVIOUSLY NOT ACHIEVABLE WITH SEMICONDUCTOR LASERS. POTENTIAL DATA MODULATION SCHEMES FOR COHERENT OPTICAL LINKS INCLUDE PULSE POSITION MODULATION, FREQUENCY SHIFT KEYING AND PHASE SHIFT KEYING. CURRENTLY, WORK IS UNDERWAY FOR A LOW DATA RATE PHASE COHERENT SYSTEM DEMONSTRATION USING BINARY PPM. THE EVENTUAL GOAL IS TO DEVELOP THE TECHNOLOGY AND SYSTEM ARCHITECTURE SUITABLE FOR HIGH DATA RATE PSK SYSTEMS.

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OTHER ACTIVITIES

- O CPM/TRELLIS ENCODING
  - O MOBILE SATELLITE APPLICATIONS
  - O OFFERS GOOD POWER PERFORMANCE AND SPECTRAL EFFICIENCY
- O CODING DIVERSITY FOR SOUND BROADCASTING SATELLITE (SBSAT) APPLICATIONS
  - O TRELLIS CODING COMBINED WITH MULTIPLE SYMBOL DIFFERENTIAL DETECTION OF MPSK HAS ADVANTAGES OVER CONVENTIONAL DIFFERENTIAL DETECTION OF CONVOLUTIONALLY ENCODED MPSK
    - O ALLOWS MORE CHANNELS TO BE ACCOMMODATED WITHIN A GIVEN BANDWIDTH AND AVAILABLE SATELLITE POWER
    - O ENABLES DIVERSITY RECEPTION
- O VARIABLE RATE MODEM FOR HIGH FREQUENCY BAND PERSONAL ACCESS SATELLITE SYSTEM (PASS)
  - O A PRACTICAL WAY TO COMBAT RAIN ATTENUATION FOR HIGH FREQUENCY COMMUNICATIONS CHANNEL

CONTINUOUS PHASE MODULATION (CPM) HAS A CONSTANT ENVELOPE AND GOOD SPECTRAL PROPERTIES, I.E., LOW OUT-OF-BAND POWER. CPM COUPLED WITH TRELLIS ENCODING CAN EFFICIENTLY UTILIZE THE AVAILABLE SATELLITE POWER AND BANDWIDTH, BOTH OF WHICH ARE PRECIOUS FOR A MOBILE SATELLITE SYSTEM.

SOUND BROADCASTING SATELLITE (SBSAT) CHANNELS SUFFER FREQUENCY AND TIME SELECTIVE FADING, WHICH CAN BE OVERCOME THROUGH CHANNEL DIVERSITY, I.E., BY PROVIDING A LARGE NUMBER OF CHANNELS THAT USERS CAN SELECTIVELY TUNE IN. TRELLIS CODING COMBINED WITH MULTIPLE SYMBOL DIFFERENTIAL DETECTION OF MPSK HAS BETTER SPECTRAL EFFICIENCY AND POWER PERFORMANCE THAN CONVENTIONAL DIFFERENTIAL DETECTION OF CONVOLUTIONALLY ENCODED MPSK, HENCE MORE CHANNELS OR SELECTION FOR A GIVEN BANDWIDTH AND SATELLITE POWER.

A PERSONAL ACCESS SATELLITE SYSTEM (PASS) OPERATING AT KA-BAND WOULD PROVIDE A DIVERSITY OF SERVICES TO USERS IN CONUS USING SMALL HAND-HELD TERMINALS. TO COMBAT THE SEVERE RAIN ATTENUATION AT KA BAND, A VARIABLE RATE MODEM (.1- 4.8 KBPS) IS BEING INVESTIGATED. THIS MODEM CAN AUTOMATICALLY DETECT AND/OR INITIATE THE CHANGE OF DATA RATE WITHOUT NETWORK COORDINATION.